Discoveries Ahead in Particle Physics

Michael Witherell

March 29, 2004

Modern Physics

Two scientific revolutions that are the foundation of modern physics occurred in the first half of the 20th Century.

These breakthroughs occurred when physicists tried to extend the laws of physics beyond everyday experience.

Relativity

To describe things moving very fast requires the theory of relativity.

Special Relativity

- We cannot catch up with light.
- Mass is a form of energy.

$$E = m c^2$$

General Relativity

- GR encompasses gravity and describes the expanding universe and black holes.

Einstein in 1905, at the age of 26

Quantum Mechanics

To describe things that are very small requires quantum mechanics.

The Heisenberg uncertainty principle:

– The more precisely we know the position of an object, the worse we know its momentum.

To describe anything as small as an atom requires the use of quantum mechanics.

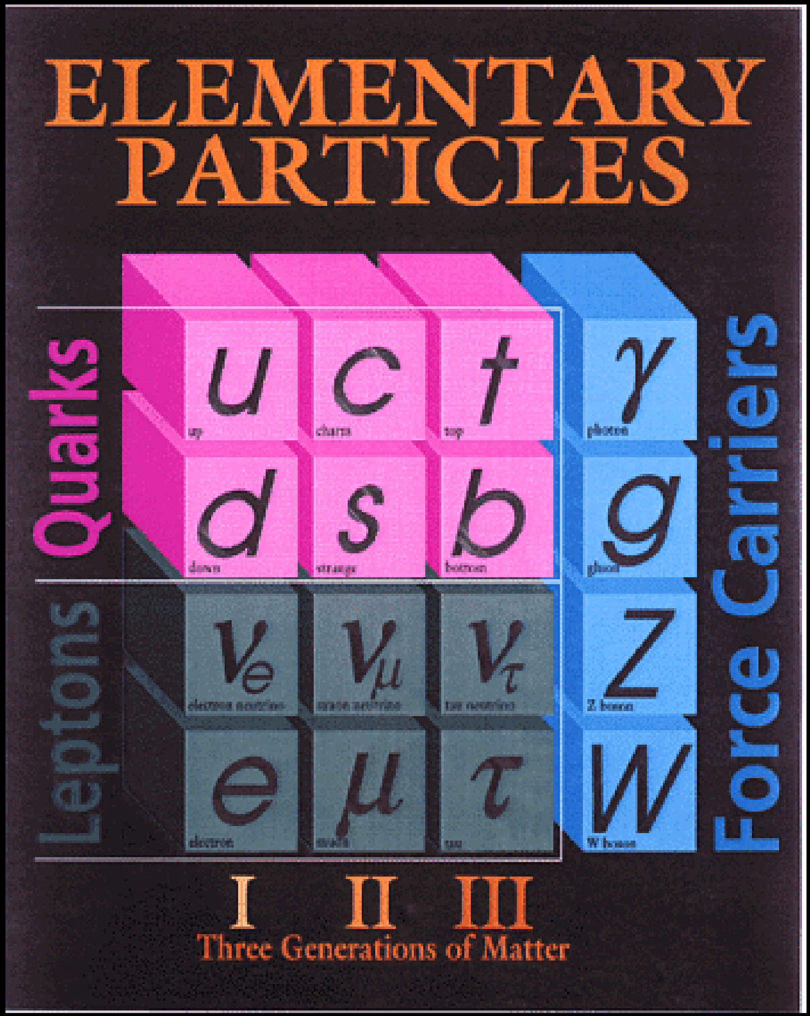
Our present theory of particle physics: The Standard Model

This is a grand intellectual achievement of the second half of the 20th Century

The theory is based on relativistic quantum field theory (QFT).

– The first QFT was the quantum theory of electricity and magnetism.

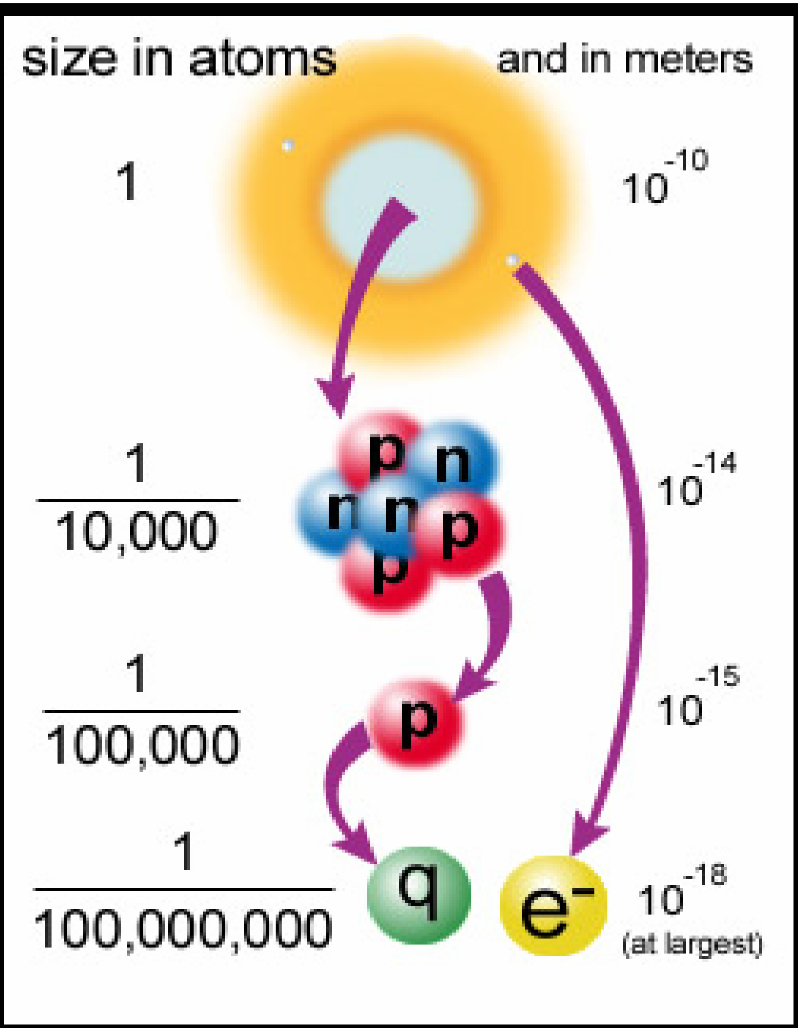
The Known Elementary Particles



The Standard Model includes quantum field theories for 3 forces: strong, electromagnetic, and weak; and 3 generations of quarks and leptons.

- Gravity famously difficult to integrate
- An effective model that breaks down at higher energy
  - We believe the energy at which the new physics turns on is of order 1 TeV.

A Sense of Scale



To resolve very small objects, we need to use very high energy. (Heisenberg again)

↓

This is why we have very large accelerators.

↑

High energy collisions also create new particles. ($E=mc^2$ again)

Quantum Mechanics and Gravity

At very small distances, Einstein's theory of gravity breaks down.

It also breaks down inside black holes.

We need another scientific revolution to reconcile quantum mechanics and general relativity.

- It will radically change our understanding of space and time.

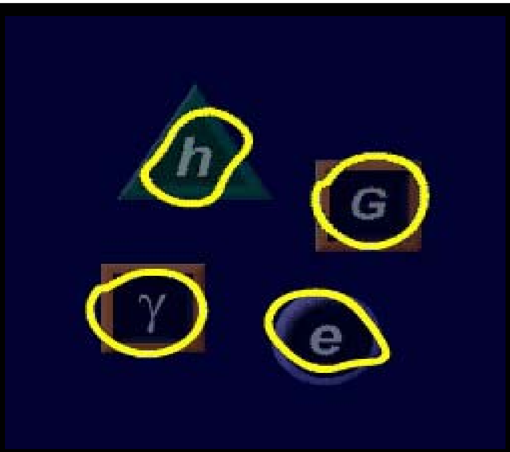
The next breakthroughs must come from experiments.

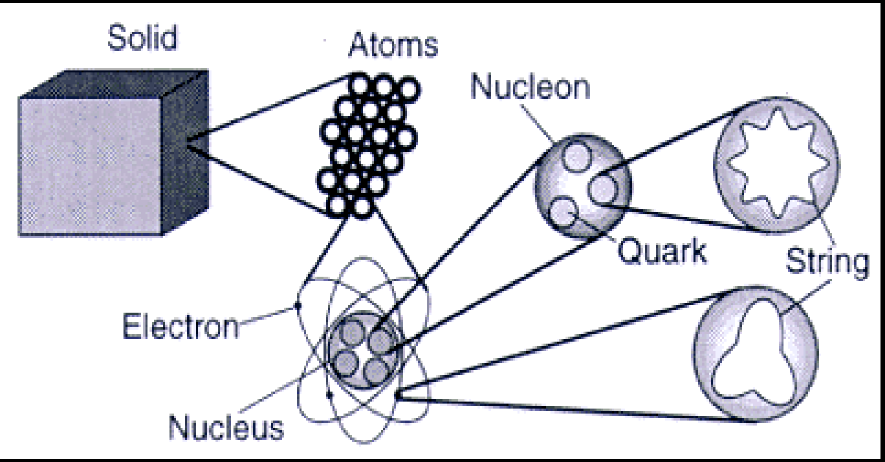
- But theory tells us where and how to look for those breakthroughs.

String Theory

String theory appears to be both a consistent quantum theory of gravity and a unified theory of all particles and forces.

– All the known particles are different vibrations of a single type of string.
– The unique theory of quantum strings needs 10 dimensions.





Some of the Great Questions of Particle Physics

Why is gravity so weak?

Are there extra space-time dimensions?

What is the nature of dark matter?

Is nature supersymmetric?

What is dark energy?

Why is any matter left in the universe?

Where does neutrino mass come from?

What causes the mysterious Higgs field?

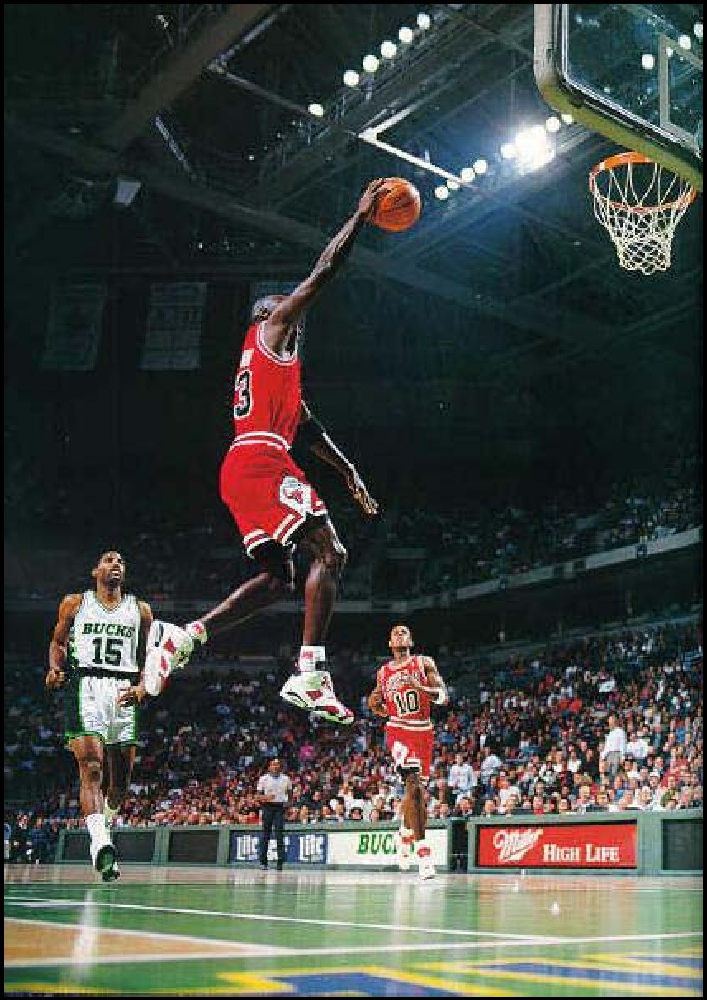
Why is gravity so weak?

The gravitational force between two electrons is 42 orders of magnitude weaker than the electrical force between them.

- 10^{42} = 1,000,000,000,000,000,000,000,000,000,000,000,000,000,000

All the other forces are about the same size as the electrical force.

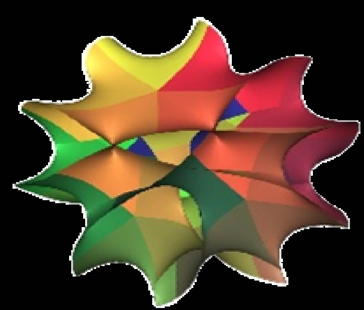
We must be missing something.



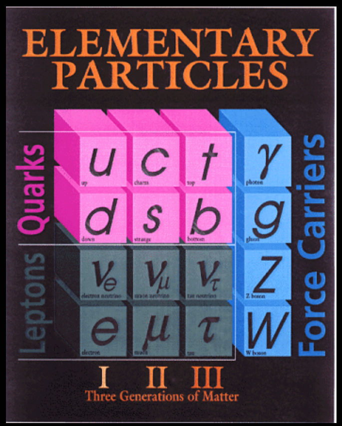
Are there extra space-time dimensions?

Why do physicists think there might be extra dimensions?

- String theory needs them.
- They can be used to disperse the intrinsic strength of gravity, making it seem weak to us.
- They would also solve other mysteries of particle physics.



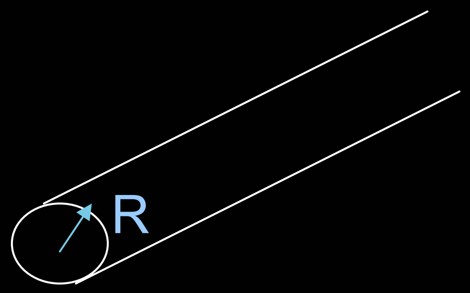
?



Extra Dimensions

The extra dimensions are hard to see, for some reason.

They might be compact and small.



1 infinite dimension
+ 1 small dimension

We used to think that the size of the extra dimensions had to be on the natural scale of quantum gravity, the Planck length ~ 10^{-35} m.

But they might be much larger, up to 10^{-18} m, and we would not have observed them with existing experiments.

Observing extra dimensions

If an extra spatial dimension is compact, coiled up with size R, we would see new massive “Kaluza-Klein” particles

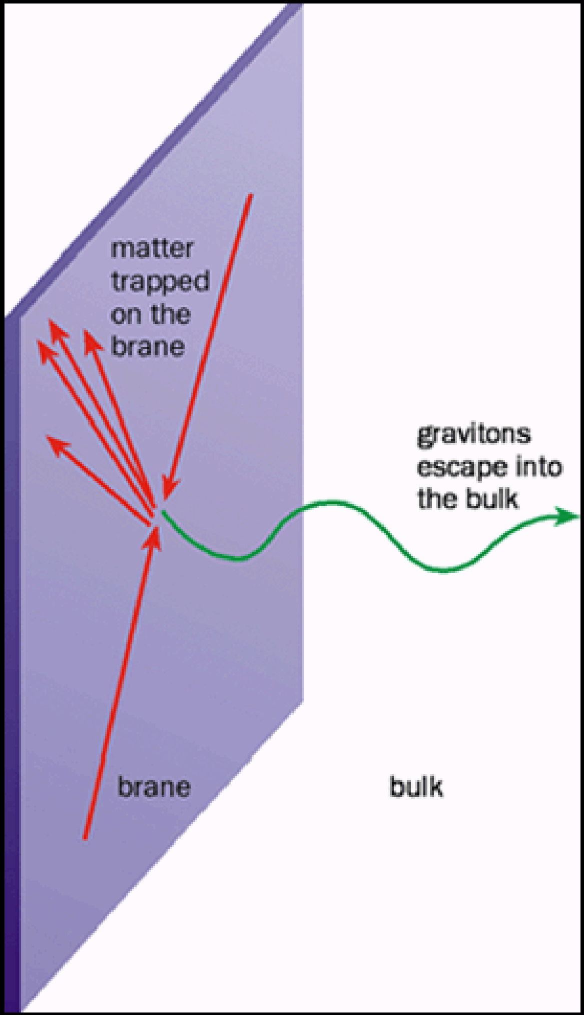
$m=1/R, 2/R, ...$

We can produce these at colliders if there is enough energy.

Life on a sheet

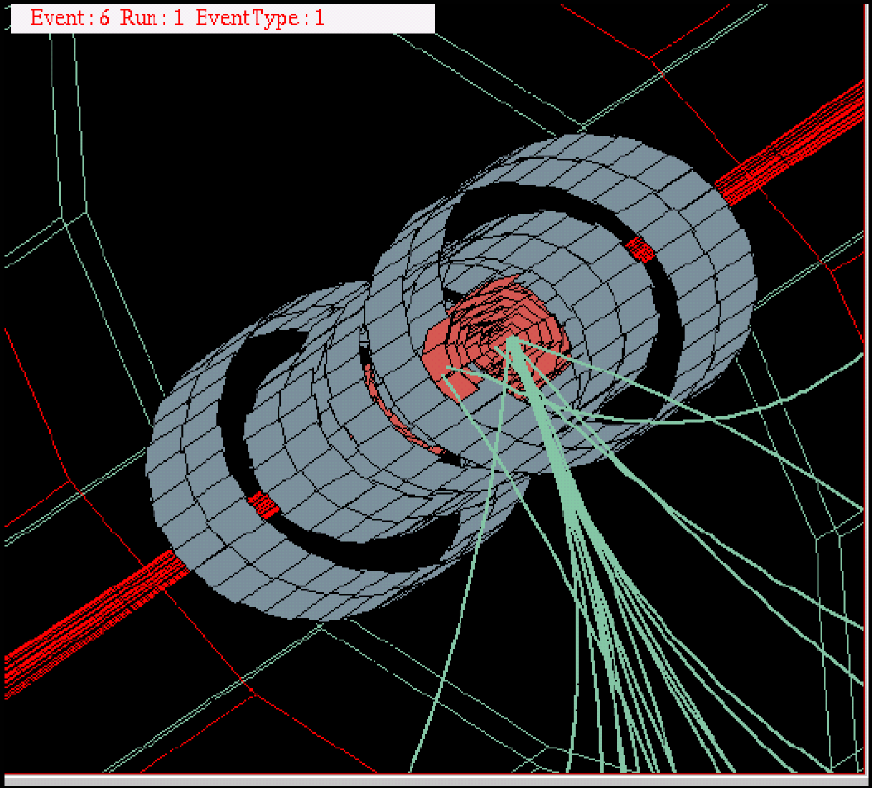
In another version, the extra dimensions are large, but we are trapped on a 3-dimensional membrane in a higher-dimensional space-time.

Only gravity acts in the extra dimensions, which can be of macroscopic size.



Extra Dimensions

- Extra dimensions required a great leap of imagination, as did quantum mechanics and general relativity.
- It would change our concepts of space and time.
- They could exist, but do they?
- If they do, they might well have the mass scale of 1 TeV.



Simulation of a K-K graviton opposite a jet of particles in the CDF detector

The first particle physics experiment: The Big Bang

10 microseconds

Quarks form protons.

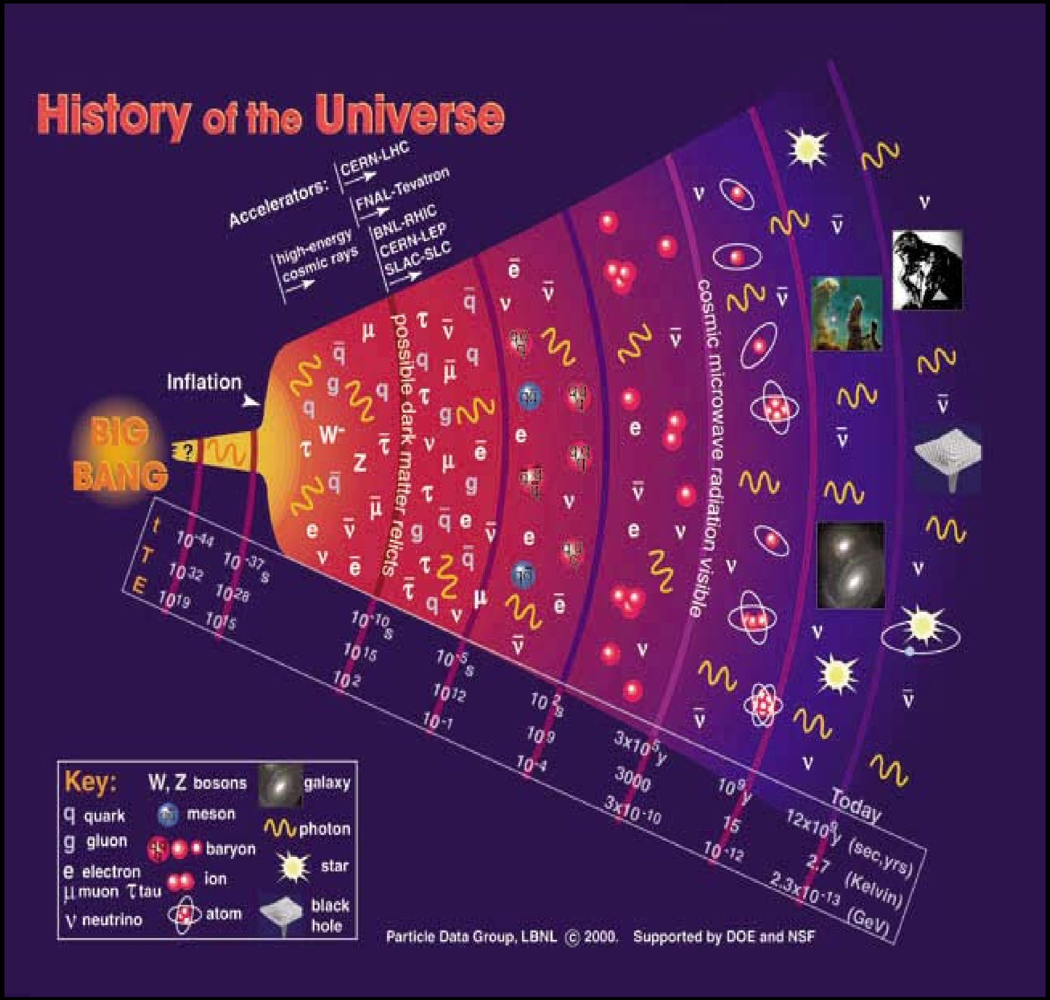
300,000 years

Nuclei capture electrons and form atoms.

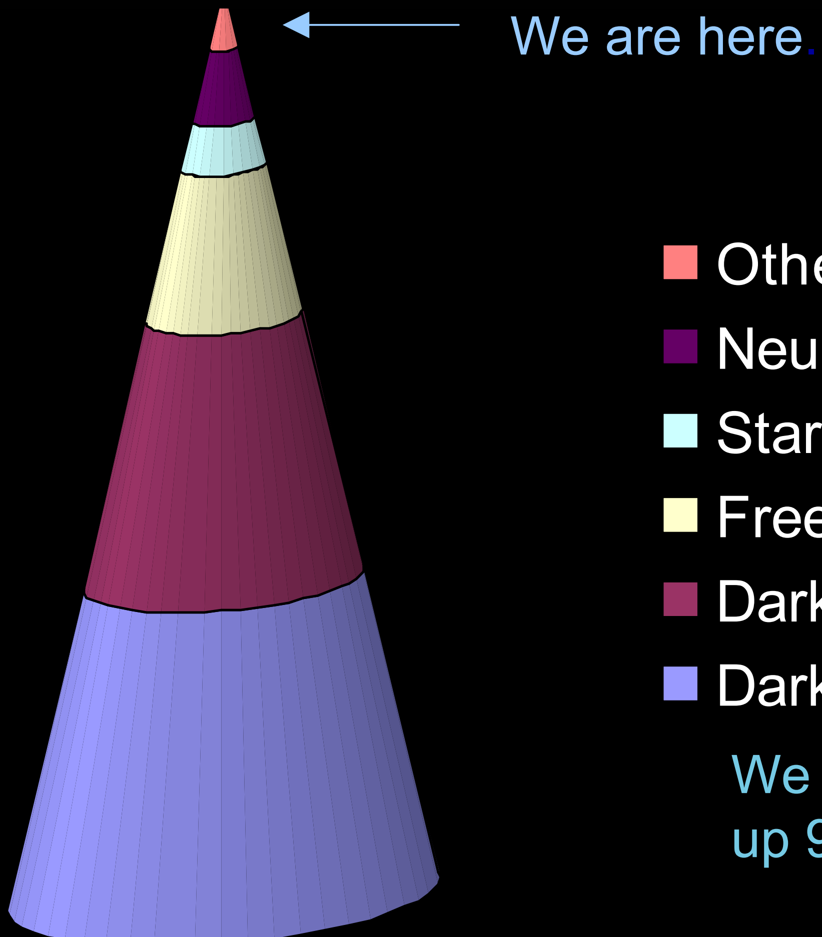
The universe becomes transparent.

13,700,000,000 years

Today



Composition of the universe



Other elements	0.03%
Neutrinos	0.3%
Stars	0.5%
Free H and He	4%
Dark matter	23%
Dark energy	72%

We do not know what makes up 95% of the universe.

Dark Matter

We see Dark Matter gravitational effects through astronomical techniques.

– Mass warps space, bending the light.

But its properties do not fit any of the standard particles.

Dark Matter is a new form of matter.

The larger, blue objects are images of a distant galaxy.
The yellow galaxy cluster in the foreground and its associated dark matter halo act as a gravitational lens.

What is the nature of Dark Matter?

To understand dark matter we need to study it in controlled experiments.

We are trying to detect its very weak interactions on earth.

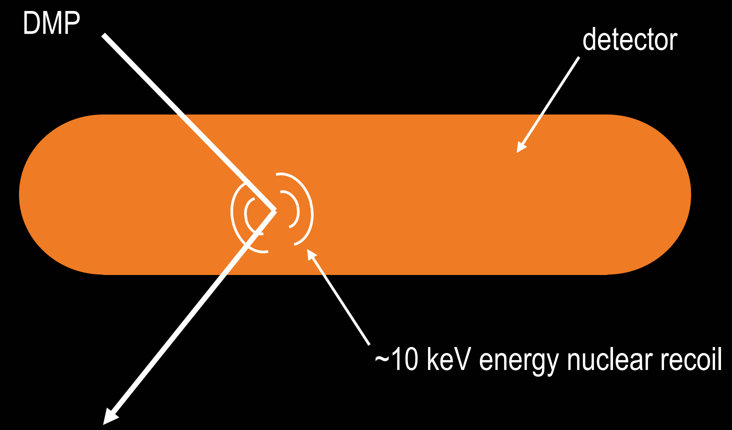
We are also trying to produce it with colliders, and identify its nature.

Catching dark matter particles in the wild

Dark matter particles are hard to see.

- 1 interaction per pound of material per year,
- Nucleus recoils with very small energy.

Very sensitive detectors designed for dark matter are operating at deep underground sites



DMP-Nucleus Scattering

Detector is a germanium crystal at 20 millikelvin, or .02 degrees above absolute zero.

Is nature supersymmetric?

"Supersymmetry, if it holds in nature, is part of the quantum structure of space and time."

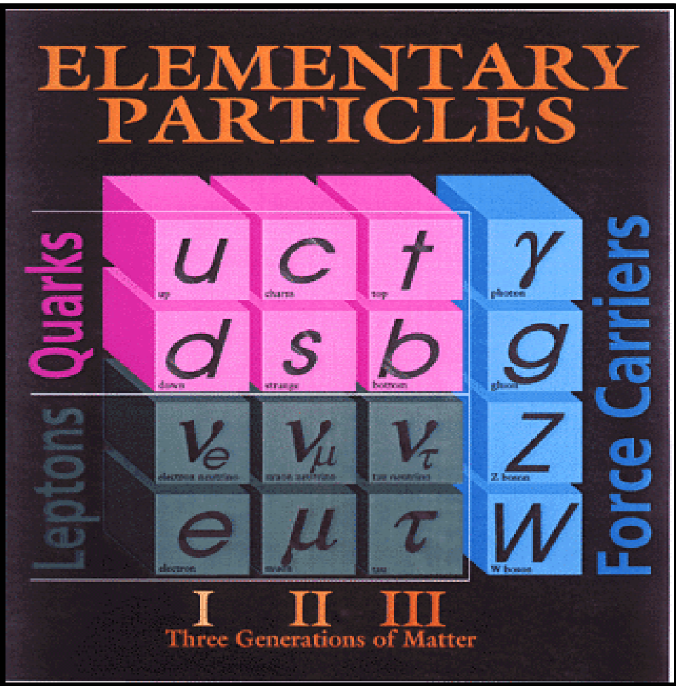
"Discovery of supersymmetry would begin a reworking of Einstein's ideas in the light of quantum mechanics."

It is a firm prediction of string theory.

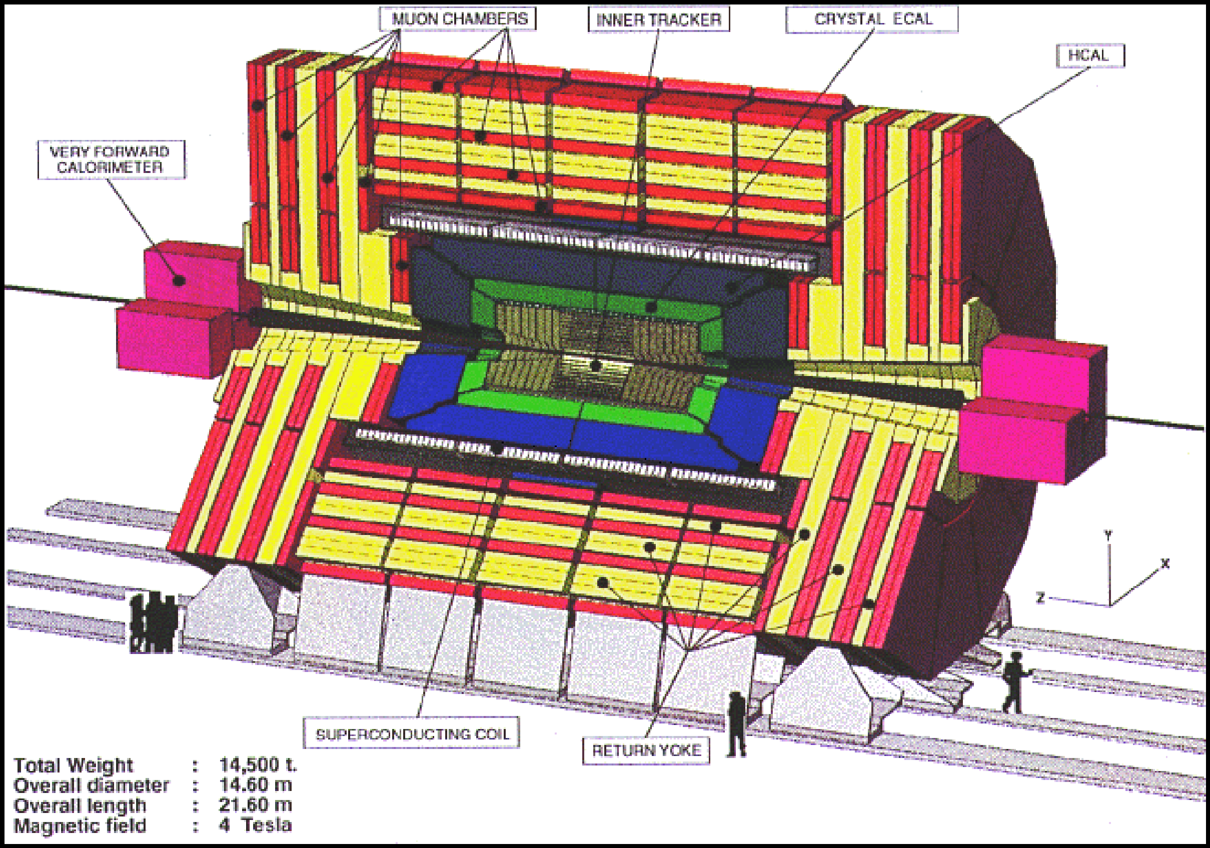
Does this elegant theory describe nature?

Only experiment can tell us.

particle	superpartner
quark	squark
gluon	gluino
photon	photino



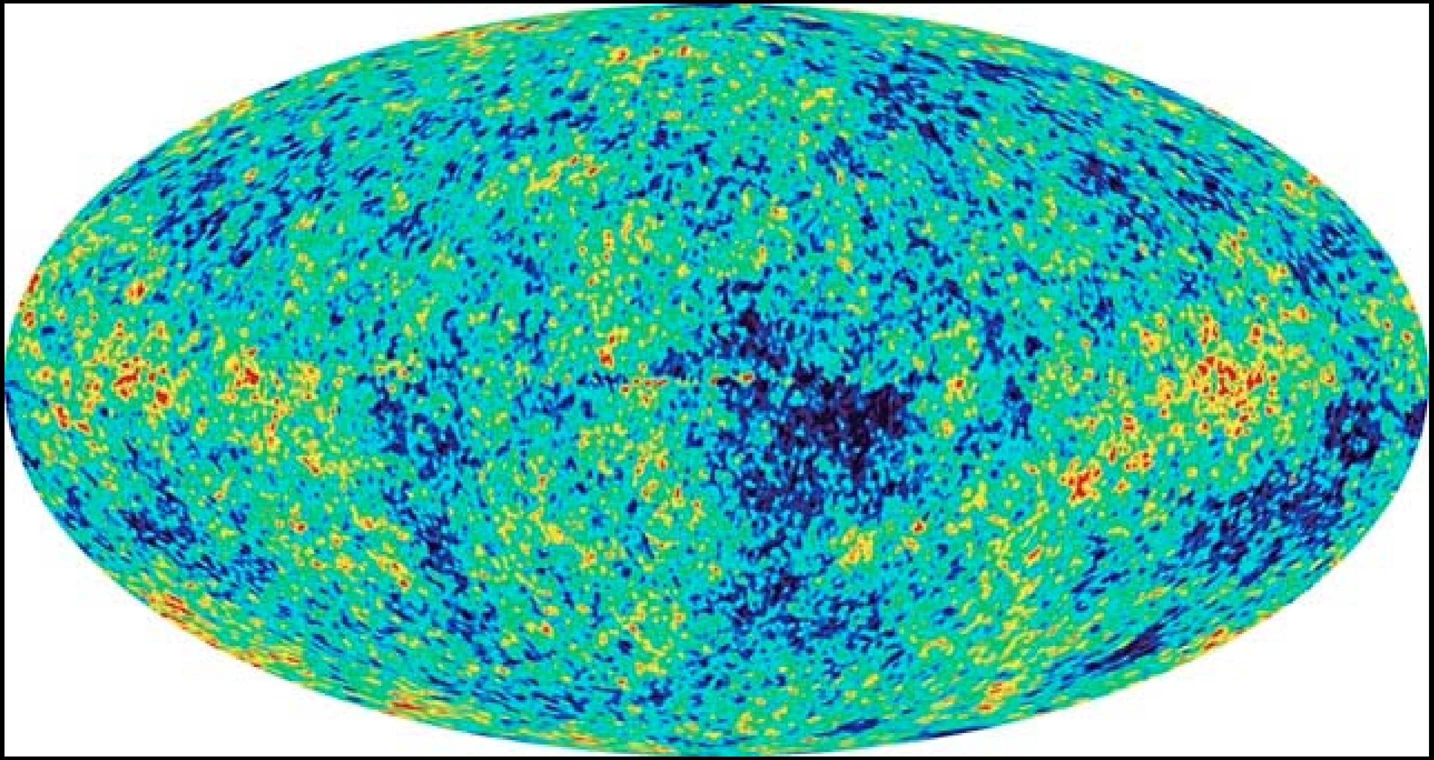
Producing and observing supersymmetric particles



If a collider has enough energy to produce supersymmetric particles, we will see them.

What is Dark Energy?

Dark energy repels matter and therefore causes the expansion of the universe to accelerate.



The Wilkinson Microwave Anisotropy Probe (WMAP) full-sky map

Quark Asymmetry in the Early Universe

Matter and antimatter were created in equal quantities in the Big Bang.
But a small asymmetry in properties led to:

10,000,000,001 quarks	10,000,000,000 antiquarks

Quarks and antiquarks got together…

Quark Asymmetry in the Early Universe

1 Quark

They have all annihilated away except for the tiny difference.

Why is any matter left in the universe?

A small asymmetry in properties between matter and antimatter left us with enough matter to form the present universe.

We know about one such asymmetry in quarks.

It does not explain the excess of matter.

New quark physics could cause the asymmetry.

Or the answer could come from the exotic world of neutrinos…

Neutrinos

Neutrinos are the strangest of the particles we have seen so far.

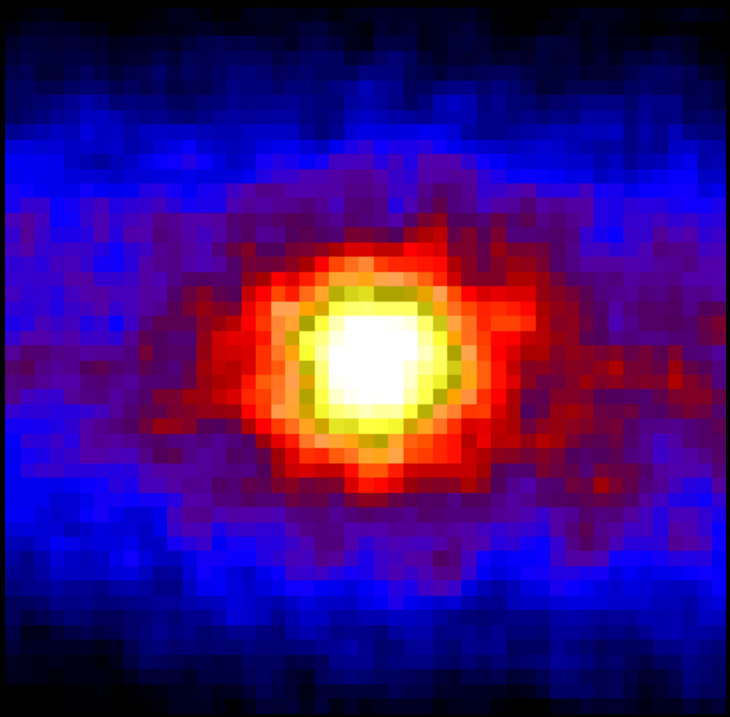
- They are very, very light.
- Matter is almost transparent to them.

Neutrinos from the Big Bang

10 million inside each of us

Neutrinos from the sun

trillions every second



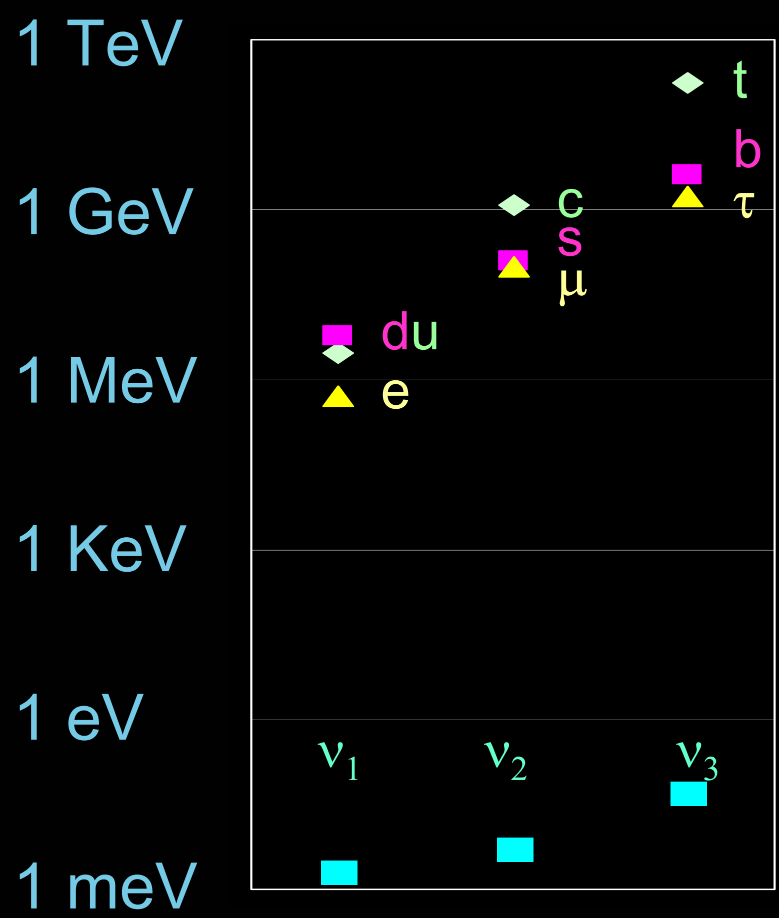
The sun as seen with neutrinos

Where does neutrino mass come from?

For about 60 years we thought neutrinos were massless, like the photon.

We now know that they have mass.

But how can the mass be so much smaller than every other mass?



Masses of the quarks and leptons

Why is neutrino mass so important?

Neutrinos are strictly massless in the Standard Model. Neutrino mass is the first sign that our existing theory is incomplete.

We believe that the very light neutrinos we see might get their mass from very heavy neutrinos with masses near 10^{15} GeV.

Decays of these heavy neutrinos in the early universe could have led to the small excess of matter that allows us all to be here today.

Long-baseline neutrinos

One observes neutrino masses by observing neutrinos change type in flight.

We will be sending muon neutrinos 730 km to Minnesota. There we will measure how many have changed into tau neutrinos.

MINOS: Interstate Neutrinos

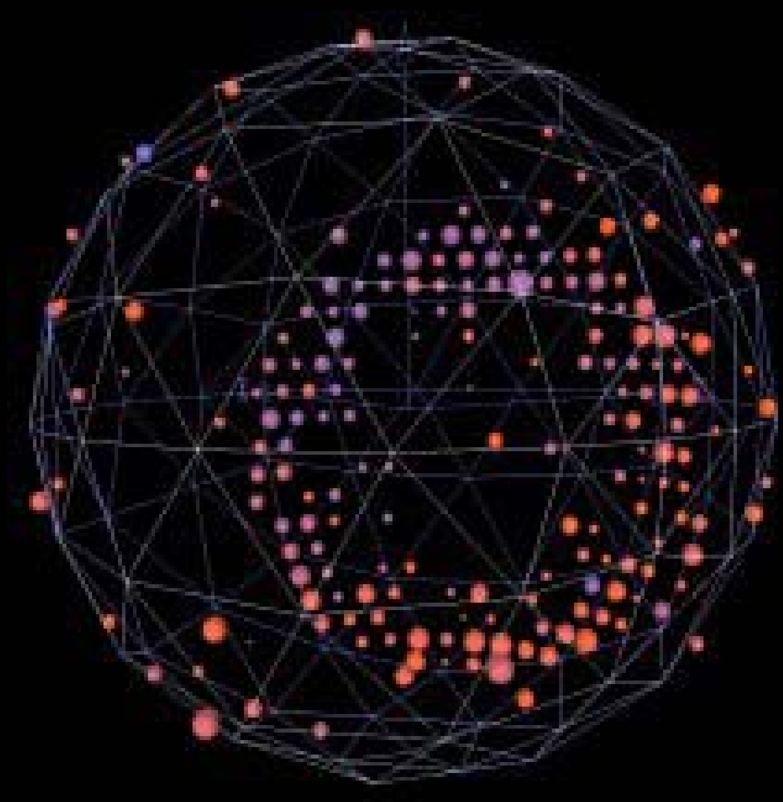
MiniBooNE

MiniBooNE is designed to follow up on evidence of a $\nu_\mu - \nu_e$ oscillation that would require a sterile neutrino.

Theorists expect no light, sterile neutrinos.

Good news: Expectations have been wrong at every step.

If MiniBooNE confirms the sterile neutrino, it will cause another neutrino revolution.

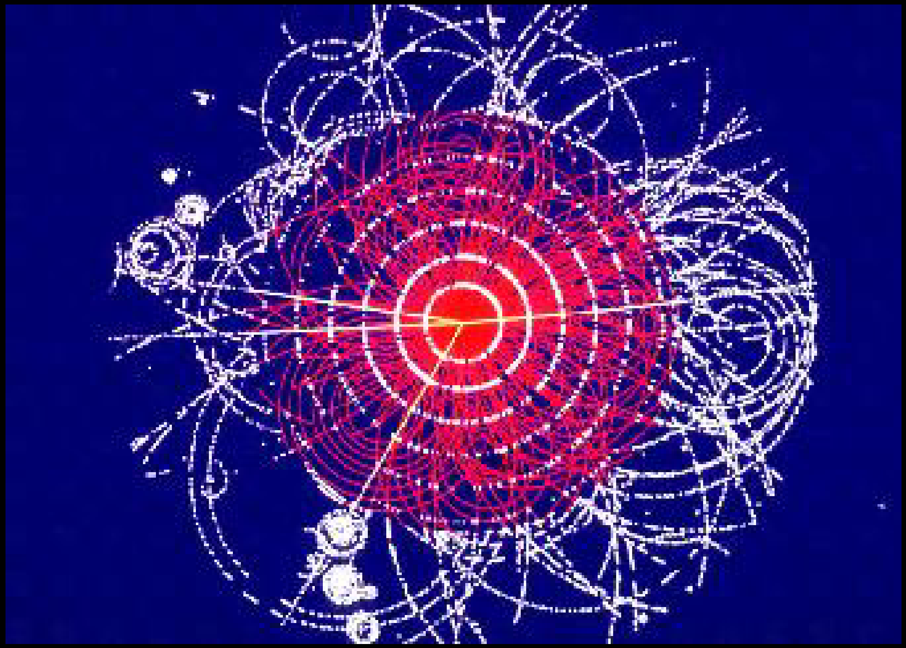


What causes the mysterious Higgs field?

The Higgs field appears to permeate space.

- We know the energy a particle gets from interacting with the Higgs fields as its mass.

The top quark feels the Higgs field most strongly.



Is there a Higgs?

Is there one?

Are there five?!

The Great Questions of Particle Physics

Why is gravity so weak?

Are there extra space-time dimensions?

What is the nature of dark matter?

Is nature supersymmetric?

What is dark energy?

Why is any matter left in the universe?

Where does neutrino mass come from?

What causes the mysterious Higgs field?

Experiment must lead.

Within 10 years the Standard Model will be replaced by a new theory of matter and forces.

- Experiment must lead the way.
  - Theory tells us what questions are the most important, but not what the answer will be.
- The change in our picture of matter and time will be revolutionary, not evolutionary.